

Laser Plasma Coupling for High Temperature Hohlraums

W. Kruer

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An Overview of Coupling Physics Issues----W. Kruer

Laser Plasma Coupling for High Temperature Hohlraums

Introduction and Overview

Simple scaling models¹ indicate that quite high radiation temperatures can be achieved in hohlraums driven with the National Ignition Facility. A scaling estimate for the radiation temperature versus pulse duration for different size NIF hohlraums is shown in Figure 1. Note that a radiation temperature of about 650 eV is projected for a so-called scale 1 hohlraum (length 2.6mm, diameter 1.6mm). With such high temperature hohlraums²⁻⁴, for example, opacity experiments could be carried out using more relevant high Z materials rather than low Z surrogates. These projections of high temperature hohlraums are uncertain, since the scaling model does not allow for the very strongly-driven laser plasma coupling physics. Lasnex calculations⁵ have been carried out to estimate the plasma and irradiation conditions in a scale 1 hohlraum driven by NIF. Linear instability gains as high as $\exp(100)$ have been found for stimulated Brillouin scattering, and other laser-driven instabilities are also far above their thresholds. More understanding of the very strongly-driven coupling physics is clearly needed in order to more realistically assess and improve the prospects for high temperature hohlraums. Not surprisingly, this regime has been avoided for inertial fusion applications and so is relatively unexplored.

Fortunately, there is reason to be hopeful. Recent high temperature hohlraum experiments on Nova^{2,3} have indicated tolerable coupling, even though quite strongly driven. It is noteworthy that a scale .25 hohlraum irradiated with Nova has plasma and irradiation conditions quite similar to those in a scale 1 hohlraum irradiated with NIF. The key issue then becomes how this coupling scales to a 4 times larger hohlraum. Recently a nonlinear scaling model⁶ has been proposed which helps us to better understand the Nova experiments and suggests a more benign scaling with plasma size than models based on linear theory. We will recommend some more detailed calculations and related experiments to help us better understand this coupling regime and determine appropriate control mechanisms.

Plasmas conditions and coupling physics issues

It is instructive to estimate the plasma conditions in high temperature hohlraums. Let's begin with the NIF point design for inertial fusion applications. the hohlraum has a peak radiation temperature of 300 ev. To minimize laser-driven instabilities, the design is restricted to a plasma fill density of about $.1 n_{cr}$, the laser intensity is limited to about $2 \times 10^{15} \text{ W/cm}^2$, and laser beam smoothing by SSD is employed. Higher temperature hohlraums will fill with plasma to a higher density, since more material is ablated by x-rays from the hohlraum walls. Estimating that the plasma density n_e scales as the x-ray mass ablation rate gives⁷ that $n_e \propto T_r^{1.86}$. Hence for a radiation temperature significantly greater than 300 ev, the hohlraum will fill to $.25 n_{cr}$ and beyond.

To be specific, let's consider a scale 1 Au hohlraum (length=2.5mm, diameter=1.6mm) driven by a 500 TW NIF pulse. If we assume that 40% of the wall area is irradiated, the intensity $I \sim 10^{16} \text{ W/cm}^2$. Using the scaling discussed above, we estimate a fill plasma density of $\sim .4 n_{cr}$. The temperature of this Au fill plasma is estimated by balancing the inverse bremsstrahlung absorption with the electron heat flow⁸, giving

$$T_e \sim (22ZL(I/2 \times 10^{13})n/n_{cr})^{.333}.$$

This temperature is about 15kev.

Improved values for the plasma conditions can be obtained from Lasnex calculations by Linda Powers⁵. Hohlraums with scale sizes from .5 to 3.5 were irradiated with 500 TW, 3 ns pulses. The beams were configured into inner and outer cones as shown in Figure 2. A characteristic density and temperature of the fill plasma at time of peak radiation temperature is shown in Figure 3. The point design for inertial fusion corresponds to scale 3.5, with density near $.1 n_{cr}$ and temperature near 5 kev. In contrast, a scale 1 high temperature hohlraum has a fill plasma density of about $.3 n_{cr}$ with an electron temperature of about 20 kev.

These Lasnex calculations do not allow for any degradation of the absorption due to laser-driven instabilities. This assumption can be tested by using a post-processor code LIP⁹, which calculates the linear gain coefficients for stimulated Brillouin and Raman scattering and laser beam filamentation. The local spatial gain rate for these instabilities is integrated along a central ray path using the Lasnex-generated plasma and irradiation

conditions. Characteristic gain exponents for SBS, SRS, and the filamentation gain per speckle are shown in Figure 4 as a function of hohlraum scale size. Note that for a scale 1 hohlraum driven with NIF, the gain exponent for SBS is nearly 100. Filamentation and SRS are also significantly above threshold.

How long should the Lasnex calculations be trusted? This so-called lifetime is quite dependent on the failure assumptions. Figure 5 shows Lasnex- calculated lifetimes as a function of scale size, displaying various criteria ranging from filling with plasma to a density of $.3 n_{cr}$ to reaching an SBS gain coefficient of 40. Improved understanding of the very strongly-driven coupling physics will enable us to better determine and control the actual constraints.

High temperature hohlraum experiments with Nova and nonlinear scaling

Initial Nova experiments^{2,3} to explore higher temperature hohlraums provide grounds for cautious optimism. In these experiments, hohlraums with scale sizes ranging from 1 to .25 were irradiated with 10 beams with a 1 ns pulse length and a total power of about 25 TW. According to Lasnex calculations, a scale .25 hohlraum driven by Nova has about the same plasma and irradiation conditions as a scale 1 driven by NIF. For example, the fill density at time of peak radiation temperature is about $.4 n_{cr}$ and the electron temperature is about 20 keV. Of course, the size of the plasma differs by a factor of 4.

Significant but tolerable levels of SBS and SRS were observed in these Nova experiments. The most detailed information³ is available for scale 5/8 and scale 3/4 hohlraums; this is shown in Table 1. Although the instabilities were nominally strongly driven, the SRS reflectivity was <15% for an unsmoothed laser beam and < 3-7% for a beam smoothed with a random phase plate. The SBS reflectivity was < 3-5% in either case. When SRS energy losses were taken into account, the measured and calculated hohlraum temperatures were in reasonable agreement.

These results are very encouraging. The key question becomes: what is the scaling to NIF? To help understand these strongly-driven Nova experiments and their scaling to NIF, a nonlinear scaling model has been recently proposed⁶. This scaling model assumes that the correlation length for stimulated scattering is set nonlinearly by laser beam filamentation and that the different scattering regions are decorrelated, as suggested by recent calculations invoking modified electron distributions. Although very idealized, the model is consistent with a number of experimental results on

the scaling of SBS with intensity, plasma density and scale length, and with the f/number of the focussing optic. See the attached paper for more details and for some additional advanced applications requiring a better understanding of very strongly-driven coupling.

Next steps

For high temperature hohlraums, we are accessing a relatively unexplored regime of laser plasma coupling. The hohlraums fill with high Z plasma with density $\sim 0.25 n_{cr}$ and with electron temperature >15 keV. The laser intensity can be quite high; $I > 10^{16}$ W/cm². Near $0.25 n_{cr}$, stimulated Raman scattering can be potent. More generally, stimulated Brillouin scattering and filamentation are very strongly driven. We also predict that the heated electron distributions will be significantly changed from Maxwellian distributions.

New calculations and related experiments are needed to better understand and control the coupling physics restraints. Let's give a few examples. Simulations using a 2D hybrid particle-in-cell code such as BZO HAR¹⁰ can quantify the competition between strongly-driven SBS and filamentation and improve our model for the nonlinear correlation length for stimulated scattering. Comparison with filamentation codes such as F3D¹¹ can help us to better mock up non-paraxial and kinetic effects in these reduced descriptions. Fokker-Planck calculations of the collisional heating and heat transport can better quantify the modified electron distributions¹². Such distributions can both change the inverse bremsstrahlung absorption coefficient by a factor of 2 (an effect already in Lasnex) and decorrelate the different scattering regions (an effect assumed in the nonlinear scaling model). Finally, calculations using particle-in-cell codes with collisions (developed by P. Rambo¹³) can more accurately determine the ion temperature including the effects of interpenetration and the ion wave damping in the fill plasma.

It would be very valuable to examine the strongly-driven regime in well-diagnosed experiments using the Janus laser. These experiments would be a natural follow-on to the many productive experiments which helped us to better understand the lower density plasma regime more relevant to inertial fusion. For example, Janus proved to be an extremely productive testbed for investigating both nonlinear beam bending¹⁴ and laser beam spraying due to filamentation¹⁵. As one example, these experiments have a sufficiently simple geometry that we could compare in detail the measurements with simulations of strongly-driven SBS and filamentation.

More experiments with smaller hohlraums could be carried with either Nova or Omega. These experiments could address the benefits of beam smoothing and low Z fill plasmas in the strongly-driven regime. Likewise, spatially-imaged measurements of the $3/2\omega_0$ and the $2\omega_0$ emission could test our calculations of hohlraum filling and assess the role of interpenetrating plasmas. Finally, hohlraums which fill to near $.25 n_{cr}$ could test our calculations of strongly-driven SRS and-as a bonus-help develop x-ray sources for other advanced applications⁶.

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Analytic NIF hohlraum limits

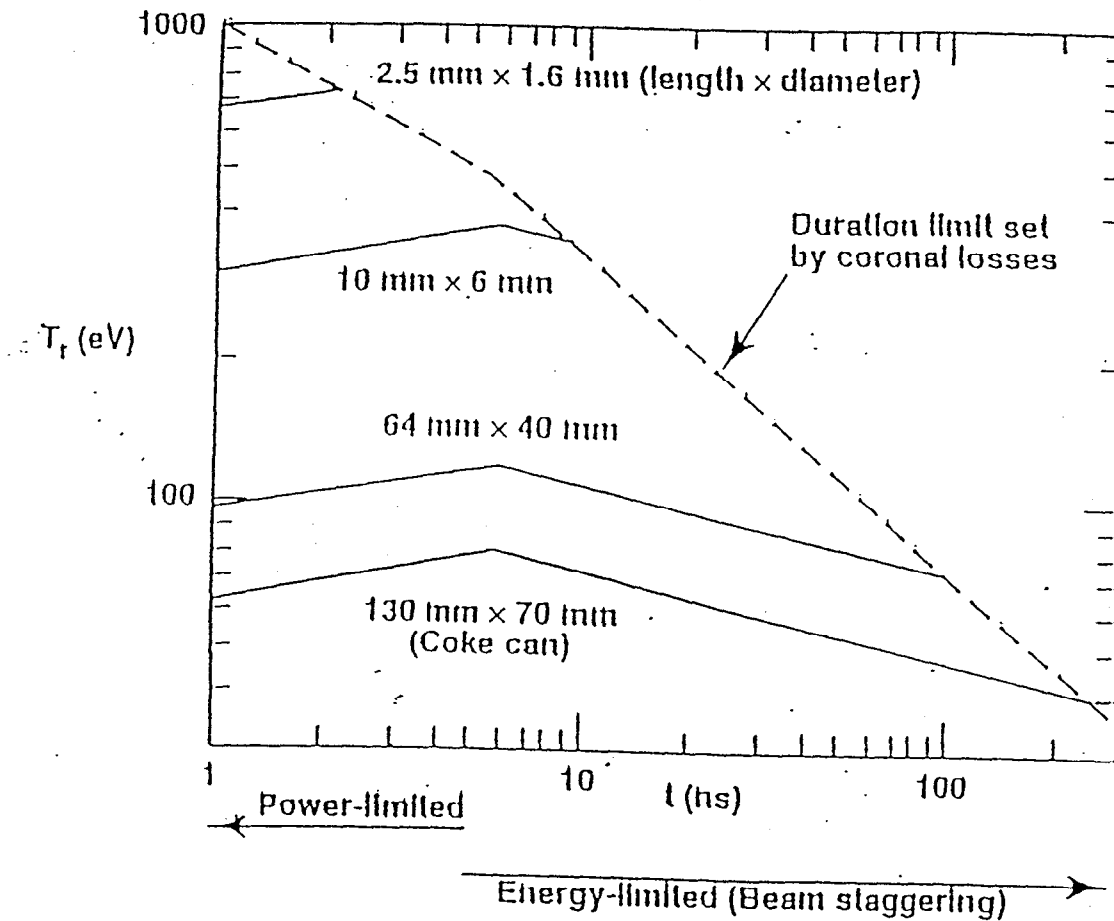


Figure 1. Scaling estimates for the radiation temperature versus laser pulse length for hohlraums of various sizes driven by NIF.

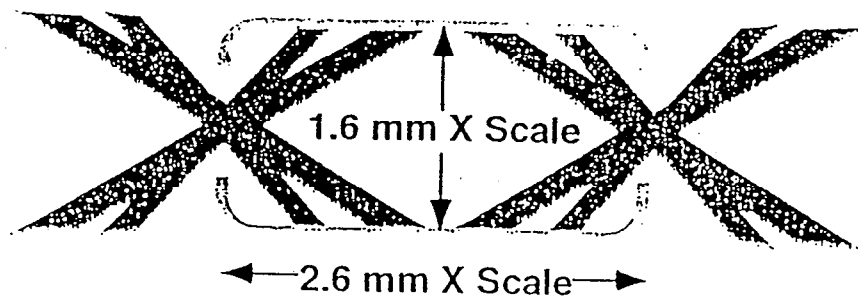


Figure 2. A schematic of the hohlraum and the irradiation scheme used in the Lasnex calculations. A 500 TW, 3 ns laser puser in 48 beams is used.

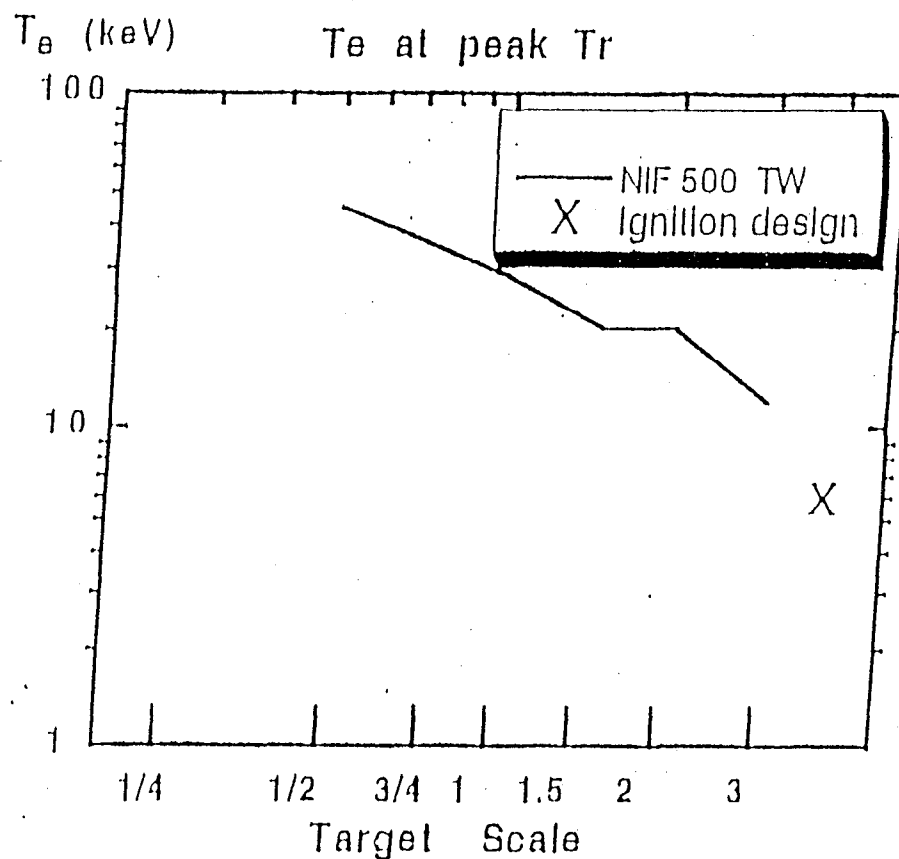
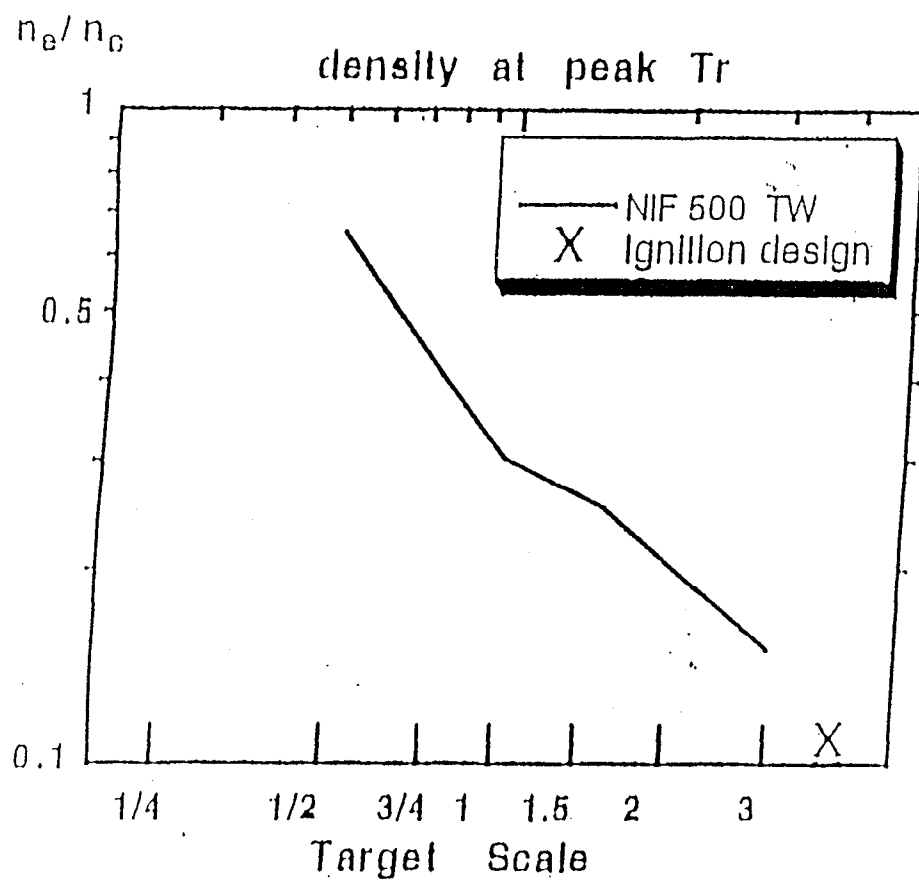


Figure 3. Lasnex calculations of the density and electron temperature of the plasma filling the hohlraum at the time of peak radiation temperature as a function of the hohlraum scale size.

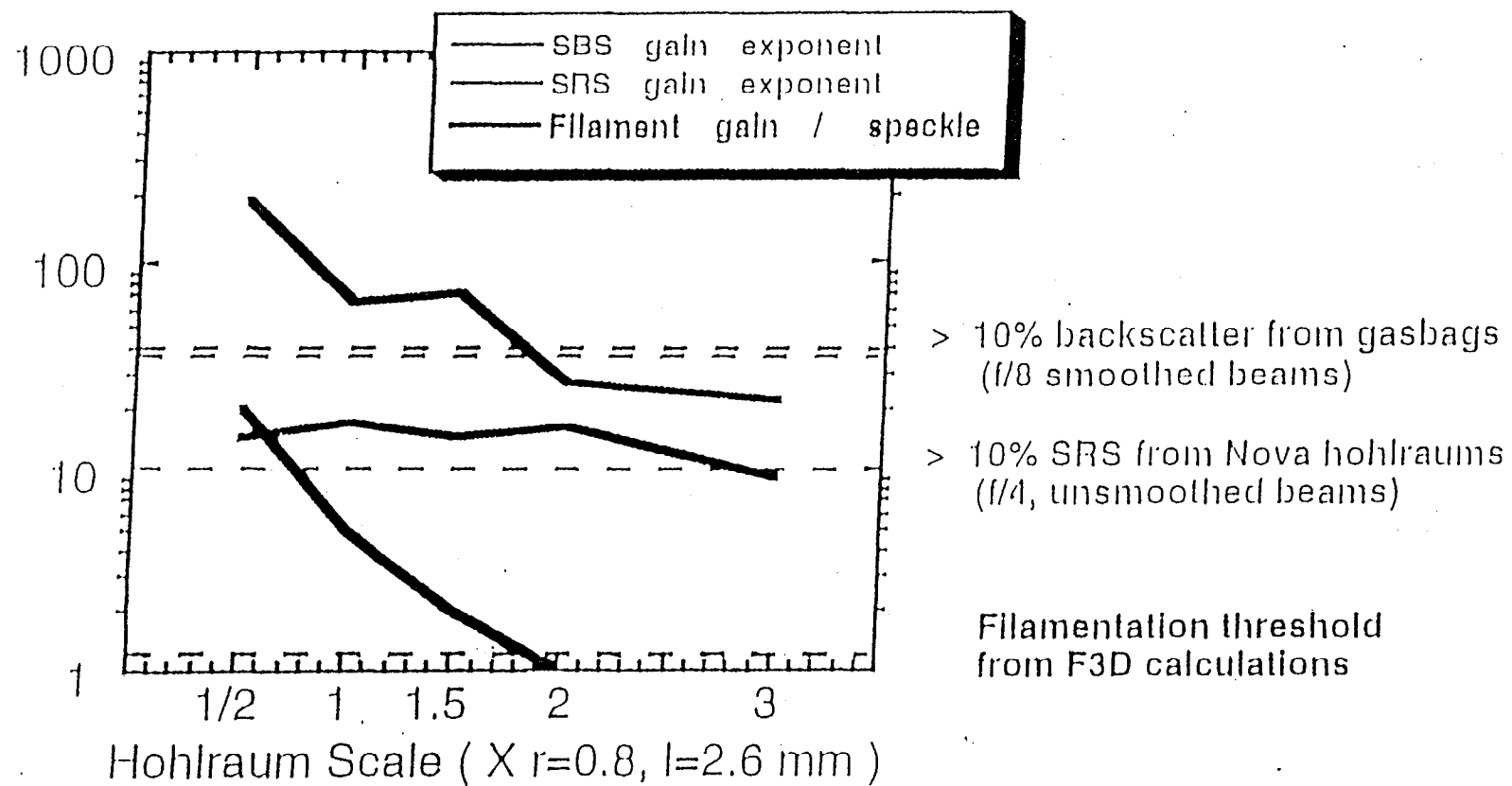


Figure 4. Laser-driven instability gain exponents calculated with the post-processor LIP at the time of peak radiation temperature as a function of the hohlraum scale size.

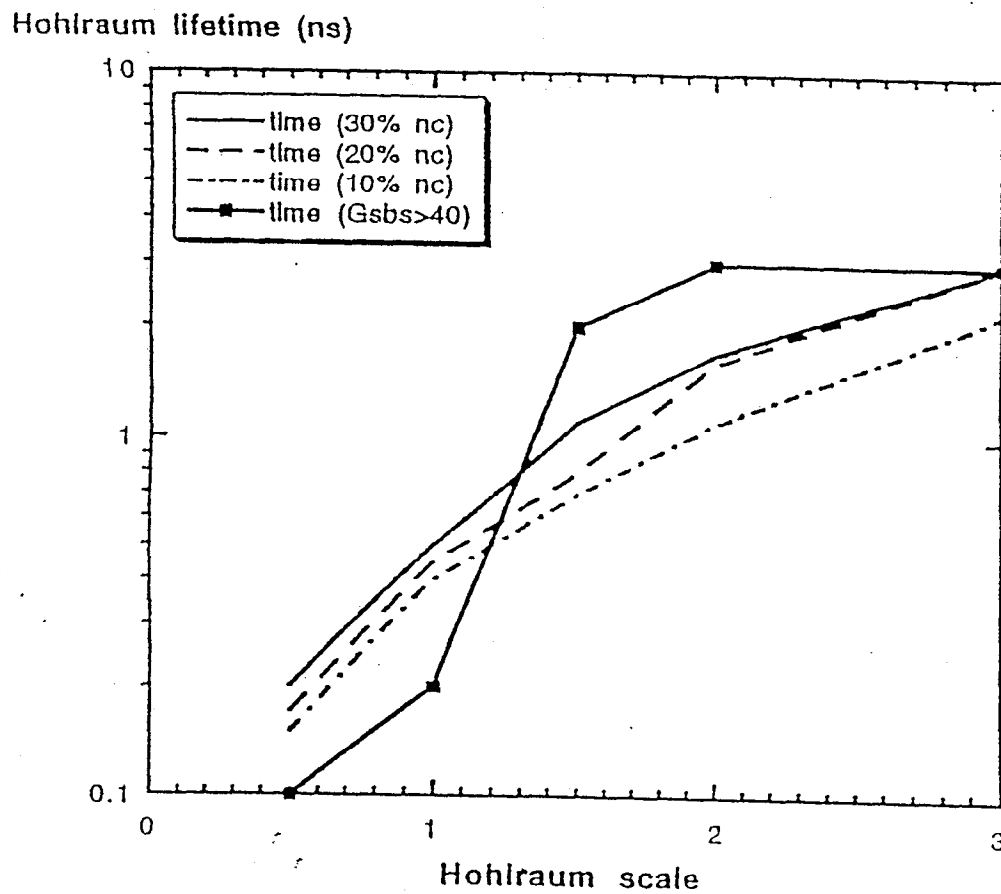


Figure 5. Lasnex-calculated hohlraum lifetimes versus scale size based on various failure assumptions.

hohlraum size/focus	T_{wall}	T_{hot}	E_{hot}	E_L	$E_{\text{srs}}/\text{beam}$	$E_{\text{sbs}}/\text{beam}$
scale-1/LEH	241 eV	41 keV	510 J	20 kJ	437 J	32 J
scale-1/ ϕ -plate	243 eV	36 keV	422 J	27 kJ	26 J	32 J
scale-3/4/LEH	273 eV	36 keV	1.3 kJ	20 kJ	455 J	78 J
scale-3/4/ ϕ -plate	261 eV	30 keV	050 J	20 kJ	48 J	76 J
scale-5/8/LEH	202 eV	40 keV	1.3 kJ	29 kJ	394 J	140 J
scale-5/8/ ϕ -plate	279 eV	40 keV	1.0 kJ	29 kJ	175 J	90 J

Table 1. Representative measurements of the radiation temperature (T_{wall}), the energy in hot electrons (E_{hot}) with temperature T_{hot} , and the energy in Raman-scattered and Brillouin-scattered light (E_{srs} and E_{sbs}).

LASER PLASMA COUPLING FOR HIGH TEMPERATURE HOHLRAUMS

LLNL

BILL KRUER

X-DIVISION / DNT / LLNL

X WORK IN PROGRESS

* # JULY 28, 1998

Some references are

Applications of High-Power Lasers to Science-Based Stockpile Stewardship (U) 1996 CLY-96-0037


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Radiation Temperature Scaling in Hohlraums for Nova and NIF

L.V. Powers, T.J. Orzechowski, P.T. Springer, L.J. Suter, B.J. MacGowan,
R.L. Berger, K.S. Budil, M.E. Foord, W.L. Kruer, A.B. Langdon,
T.S. Perry, M.D. Rosen, T.D. Shepard, C.H. Still and E.A. Williams
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D. Desenne, A. Dulleu, and D. Juraszek
Centre d'etudes de Limeil-Valenton

Presented by:
Linda V. Powers
Target Design and Theory
Hohlraum Dynamics

 University of California
Lawrence Livermore
National Laboratory



Presented at:
24th European Conference on
Laser Interaction with Matter
Madrid, Spain
June 3-7, 1996

Energetics of small, high-temperature, laser-driven hohlraums

T. J. Orzechowski, B. B. Afeyan, R. L. Berger, M. A. Blain, R. K.
Kirkwood, H. N. Kornblum, W. L. Kruer, B. J. MacGowan, J. D. Moody,
L. V. Powers, M. D. Rosen, P. T. Springer, L. J. Suter, R. L. Wallace



Presented at the 26th Anomalous Absorption Conference
Fairbanks, AK
26-30 August, 1996

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W-7504-ENG-48

Some references are

-----LLNL

Experiments to Investigate High Temperature Hohlraum
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Scaling for Hohlraum Limits Memo, 1998

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Rosen,...

Science on High-Energy Lasers: From Today to the NIF
UCRL-ID-119170, 1995

R.L. Lee, R. Petrasso, R.W. Falcone

Outline of Presentation

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*Nova experiments and scaling models indicate that higher temperature hohlraums are possible with NIF; these are valuable for SSMP

*Strongly-driven laser plasma interaction physics is a key issue for attaining higher temperature hohlraums

*Nova experiments and recent theory are hopeful: next steps are outlined

Applied High Energy Density Science Problems: II. Weapons Physics

Laboratory experiments test weapons physics issues

Weapons physics and related stockpile stewardship experiments carried out on ICF facilities are collaborative efforts carried out by ICF and weapons program personnel. The role played by the ICF Program is generally twofold: (1) to expand the range of high energy density plasma conditions (hohlraum temperature; plasma lifetime, density, and temperature) accessible in the laboratory, and (2) to define new experimental geometries, techniques, and diagnostics that facilitate stewardship experiments. Laboratory experiments to test particular weapons issues are then carried out in collaboration with weapons program scientists.

Weapons physics scaling

Similar to ignition physics, weapons physics experiments on ICF facilities involve the study of both basic and applied high energy density science problems. Some of these experiments will be proof of principle efforts for larger scale experiments on future ICF program facilities that will be carried out in a regime more comparable to weapon conditions. In particular, the scaling of these experiments to NIF and potential future pulsed power facilities is of high priority, as these capabilities will be required in the near term to maximize the utility of the ICF Program to stockpile stewardship.

Plans for fundamental high energy density science research relevant to weapons include:

Hydrodynamics. Planar experiments on Nova, Omega, and Nike will investigate the transition to turbulence. The formation of jets will be studied using hemispherical and other targets.

Atomic Physics and Radiative Properties. Measurements of mid-Z material opacity will continue on Nova and PBFA Z, and begin on Nike. Preparatory work for NIF opacity experiments such as x-ray backlighter development will also continue. New atomic physics modeling capabilities are under development at LLNL, LANL, and NRL.

Material Properties and Equation of State. Methods for measuring on- and off-Hugoniot equations of state to the few percent accuracy required to differentiate between theories will be developed. The use of flyer plate techniques to achieve very high pressures (pressures near ~ 1 Gbar have been observed to date) will be explored.

Plasma Physics. Plasma physics issues relevant to important goals, such as the achievement of hohlraums with temperatures greater than 300 eV, will be investigated.

Computational Physics. The ICF Program will continue development of advanced three-dimensional simulation codes, as described further below.

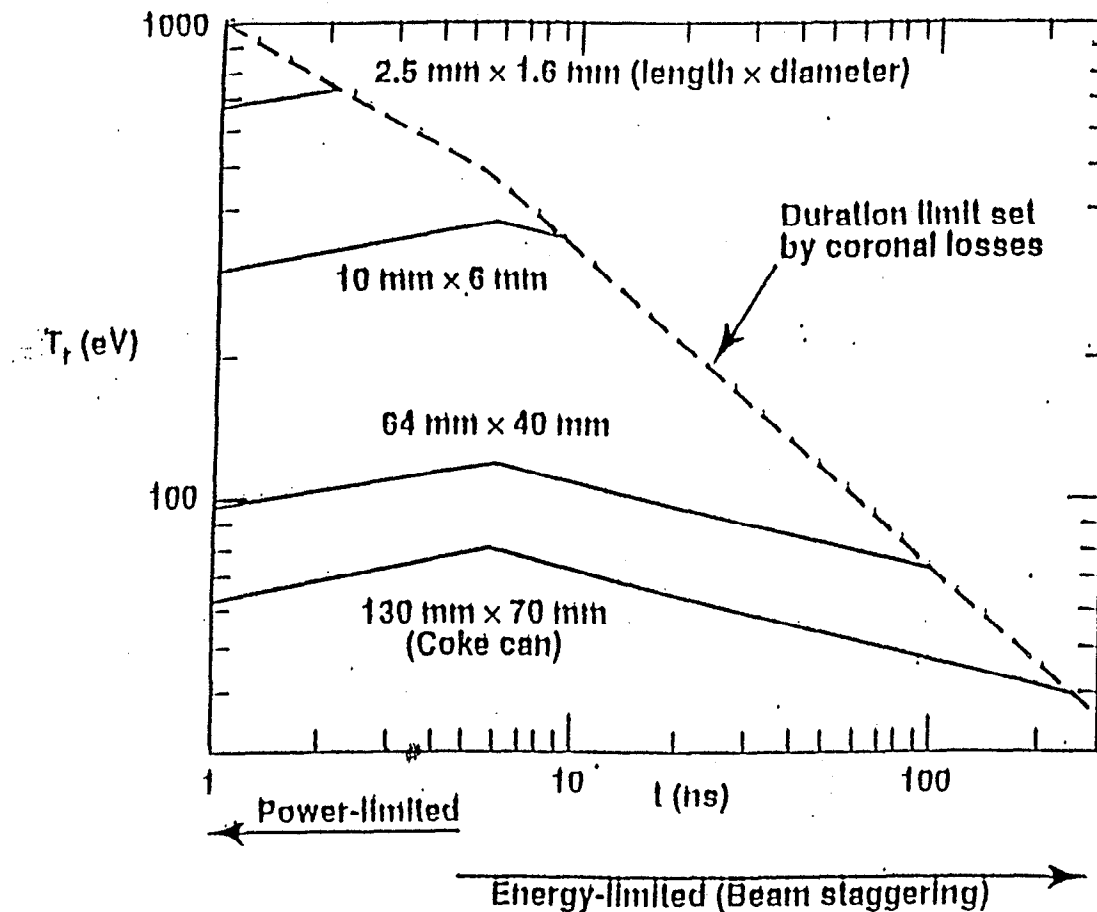
Specific applied problems to be considered include:

High temperature hohlraum development. Hohlraums with drive temperatures well in excess of 300 eV are of interest to the weapons program for hydrodynamic studies and other experiments; efforts to develop such radiation environments will be carried out on Nova.

The NIF will explore a wide range of hohlraum sizes and temperatures



Analytic NIF hohlraum limits



Outline of Presentation

-----LLNL

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- *Nova experiments and recent theory are hopeful: next steps are outlined

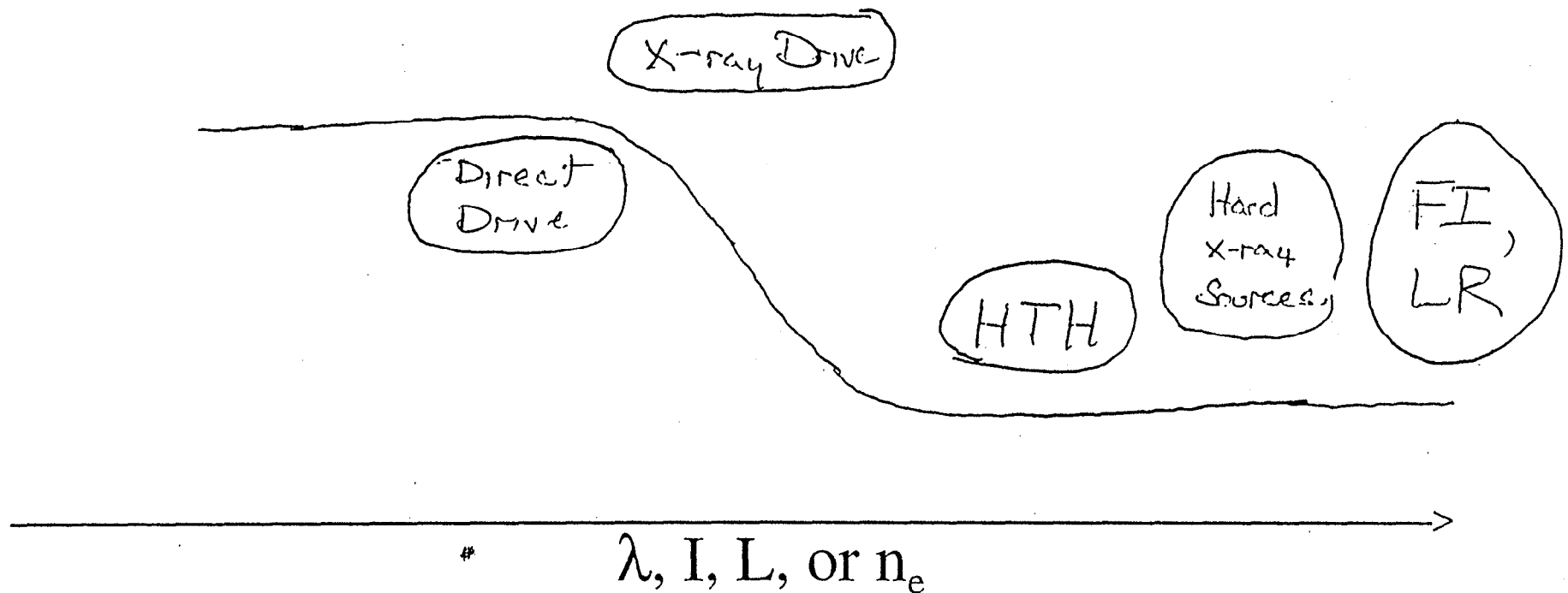
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The Big Picture

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Collisional Coupling

Nonlinear Coupling



Mainline ICF: stay to the left

Many advanced applications are to the right

Nonlinear coupling physics is needed for high temperature hohlraums

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$$n_e \sim T_r^{1.86} \quad \text{JDL Eq.7-28}$$

NIF point design

SRS, $2\omega_{pe}$

SBS, FIL

$$n_e = .1 n_{cr}, T_e = 5 \text{ keV}$$

$$.25 n_{cr}$$

$$>.25 n_{cr}$$

$$\text{SSD, } I = 2 \times 10^{15} \text{ W/cm}^2$$

Bonus-hard
x-rays

300 eV

#

T_r

----->

Simple estimate of plasma conditions in NIF Scale 1 HTH

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Scale 1 2.5 mm x 1.6 mm

1.
$$I \sim \frac{500 \text{ TW}}{.4 (.04\pi) \text{ cm}^2} \sim 10^{16} \text{ W/cm}^2$$

2.
$$n_e \propto T_r^{1.86}$$

scales as areal mass density
ablation by x-rays

3.
$$T_e \approx \left[22.2 \left[\frac{I}{2 \times 10^{13} \frac{n}{n_{cr}}} \right]^{1/3} \right]^{1/3}$$
 Inverse bremsstrahlung heating

1, 2 and 3 \rightarrow
$$n_e \approx .4 n_{cr}$$

$$T_e \approx 15 \text{ keV}$$

Lasnex calculations have been used to estimate the plasma conditions for high temperature hohlraums



We have begun to evaluate a range of NIF hohlraum designs at small target size and high laser power

Target:

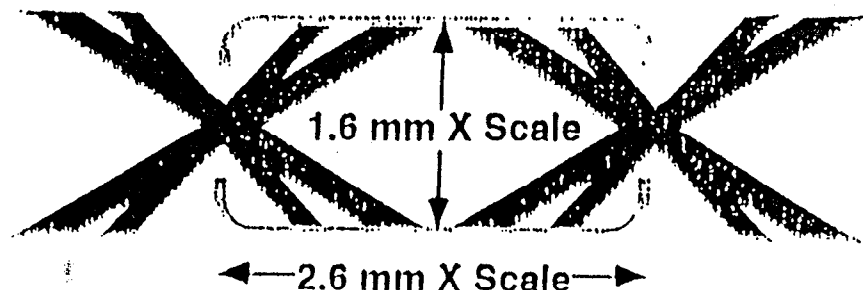
Scales 1/2, 1, 1.5, 2, 3
(X r=0.8mm, l=2.6mm)

Laser:

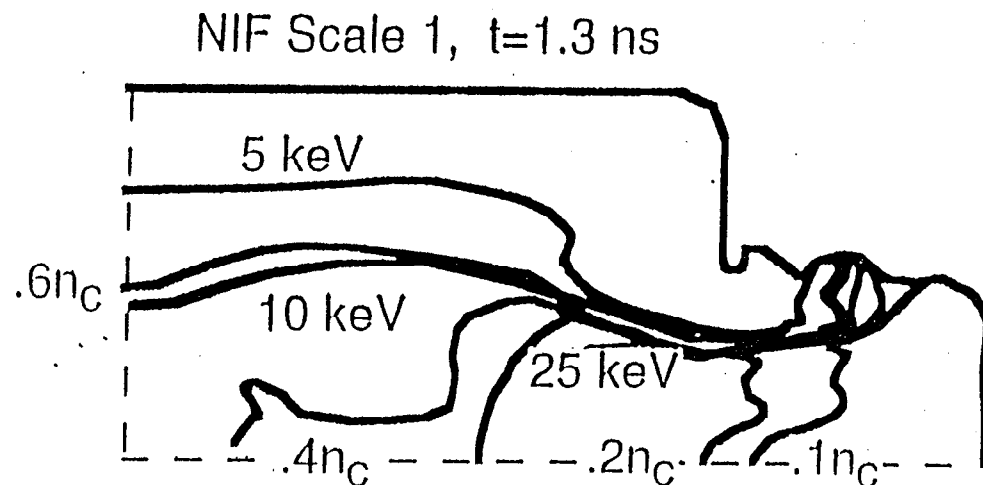
500 TW / 3ns in 48 beams

Inner cone spotsize = $D_{\text{leh}} / 2$

Outer cone spotsize = $D_{\text{leh}} / 3$

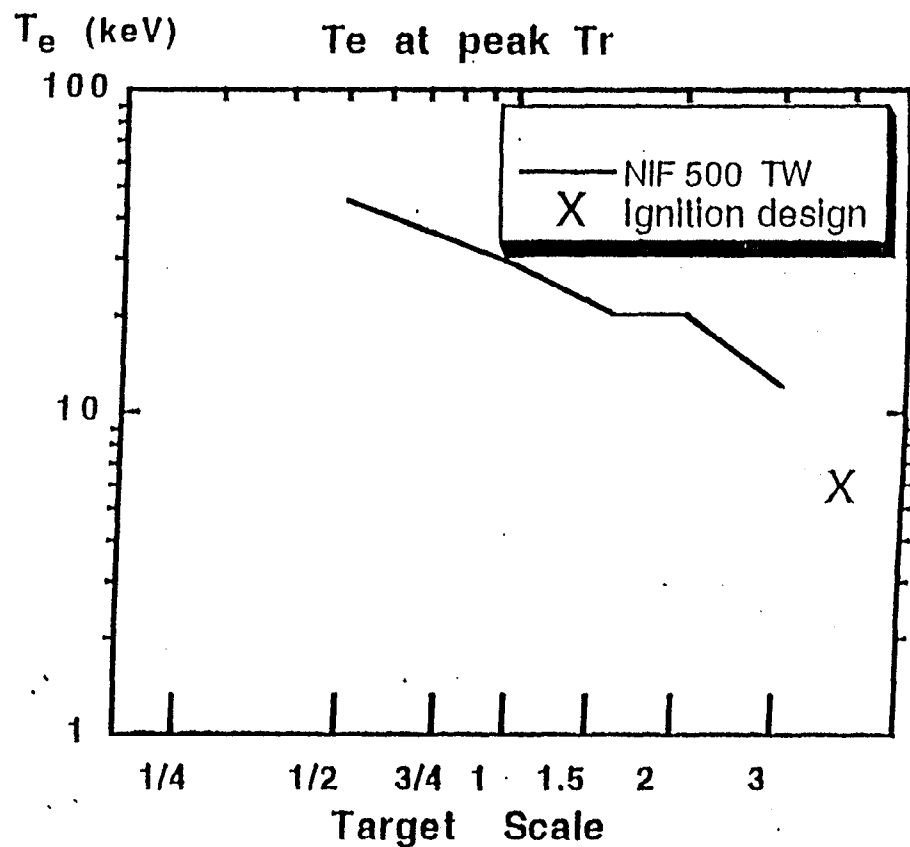
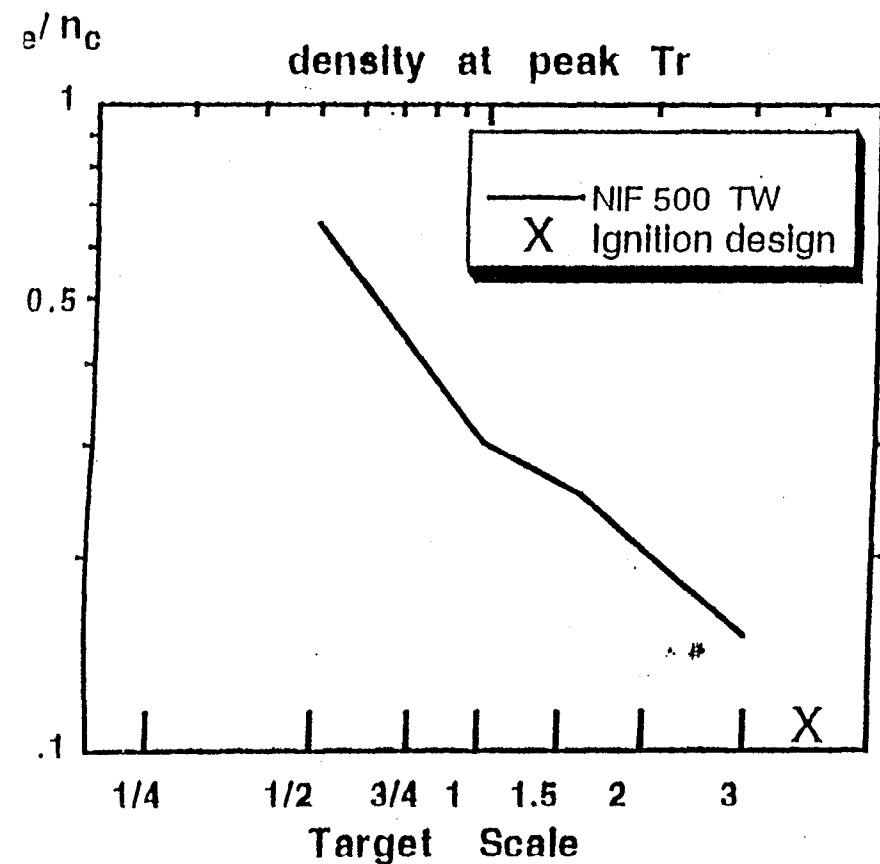


The fill plasma in these targets^{,#} is hot and dense by the time of peak radiation flux*



NIF high temperature hohlraums fill with hot plasma
with density $\gtrsim .25 n_{cr}$

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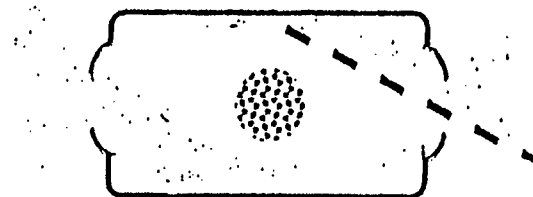


Powers

We use the calculated linear gain exponents and associated SRS and SBS reflectivities to assess the probability of significant parametric instabilities



We integrate the local spatial gain rate calculated from simulation parameters along the path of the scattered light to obtain the intensity gain exponent



$$G(\omega_s) = \int_{\text{path}} dz \frac{(k_o - k_s)^2 v_o^2}{4 \omega_o v_g} \text{Im} \left(\frac{(1 + \chi_i) \chi_e}{1 + \chi_i + \chi_e} \right)$$

The LIP calculation includes:

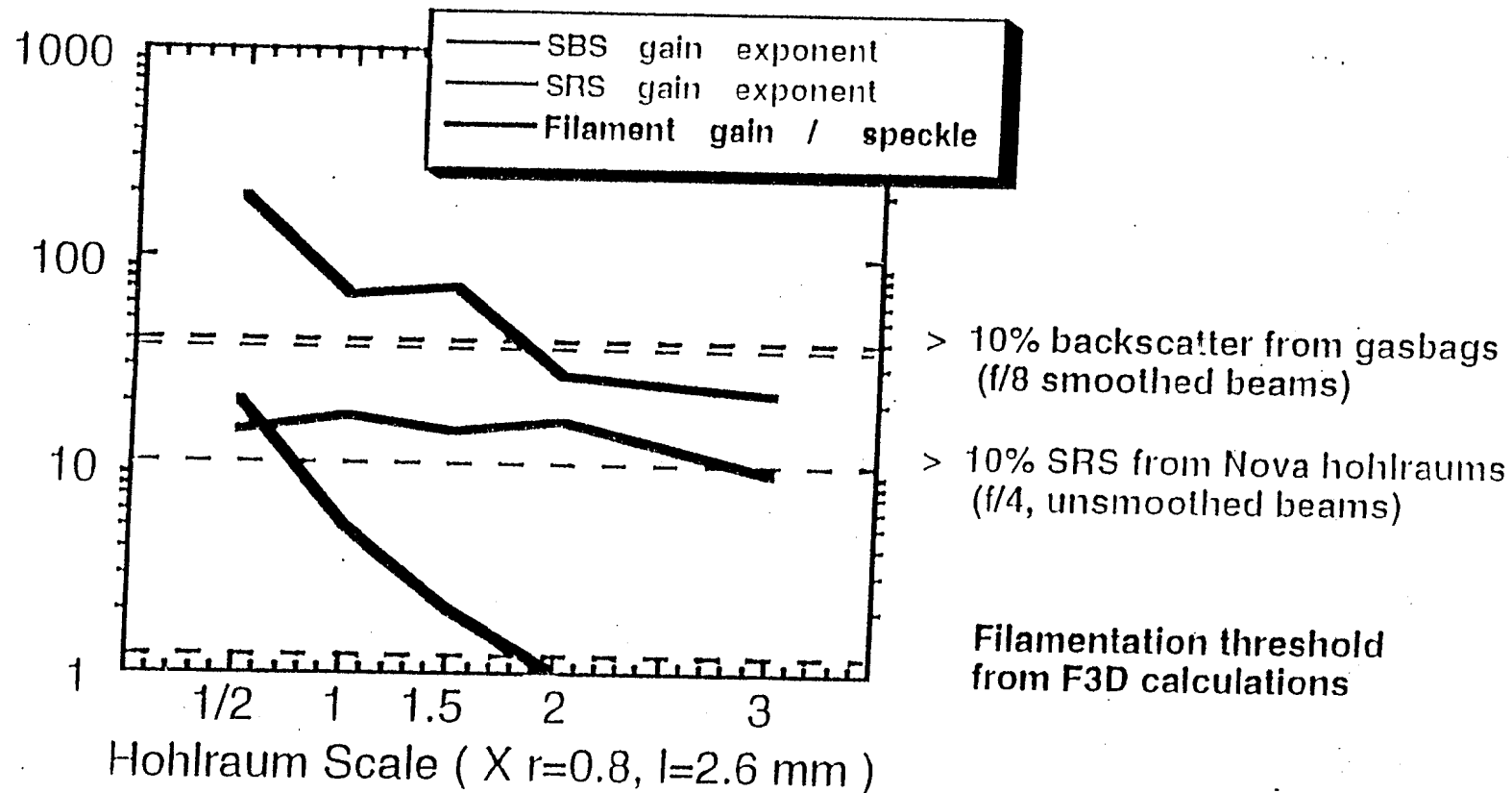
- kinetically correct growth rates
- multi-species ion damping
- intensity variations due to Inverse Bremsstrahlung absorption and beam divergence
- pump depletion limit on reflectivities

LIP does not treat

- nonlinear saturation / detuning
- beam coherence effects (speckles, temporal smoothing)

Complementary modeling and analysis techniques are used to investigate effects not included in this simple treatment

In small NIF hohlraums driven with 500 TW power, calculated gains for SBS and filamentation are well above thresholds estimated from experiment

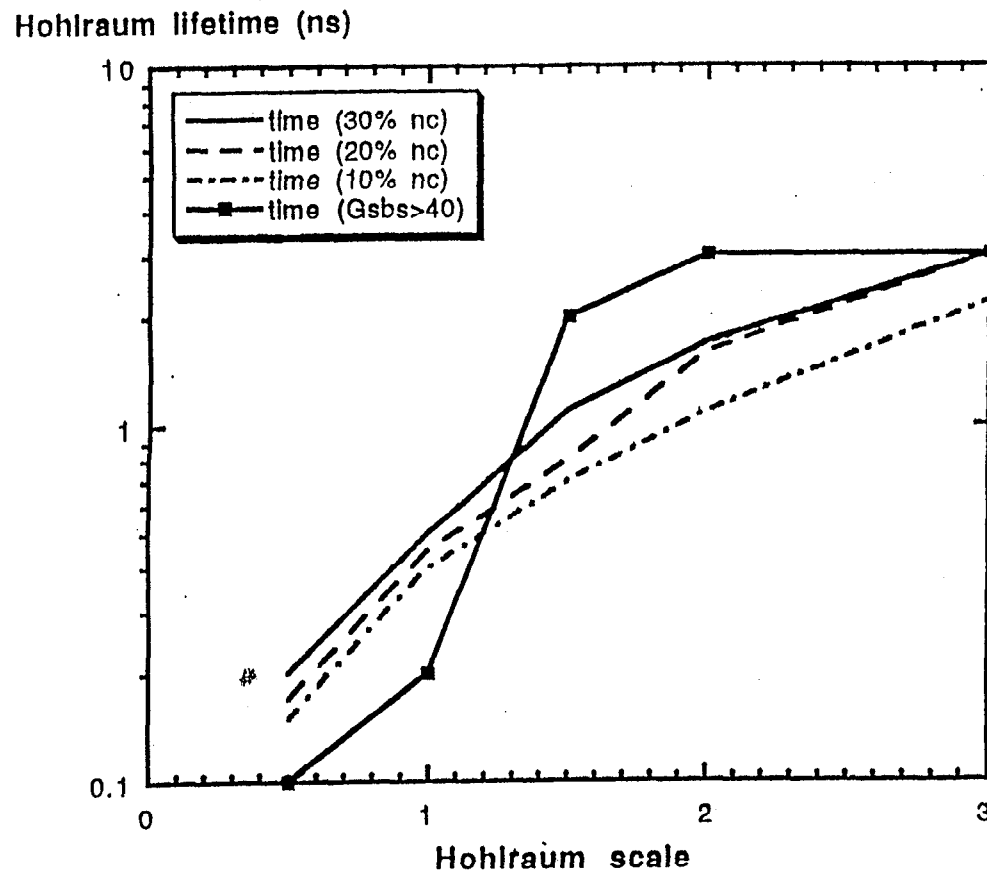


- SBS and filamentation gains decrease as hohlraum size increases due to lower intensity and fill density
- SRS gains scale weakly with target size because larger hohlraums have more plasma with $n_e \sim 20\% n_c$ and are cooler

Life times for NIF hohlraums depend on failure assumptions

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Powers



Outline of Presentation

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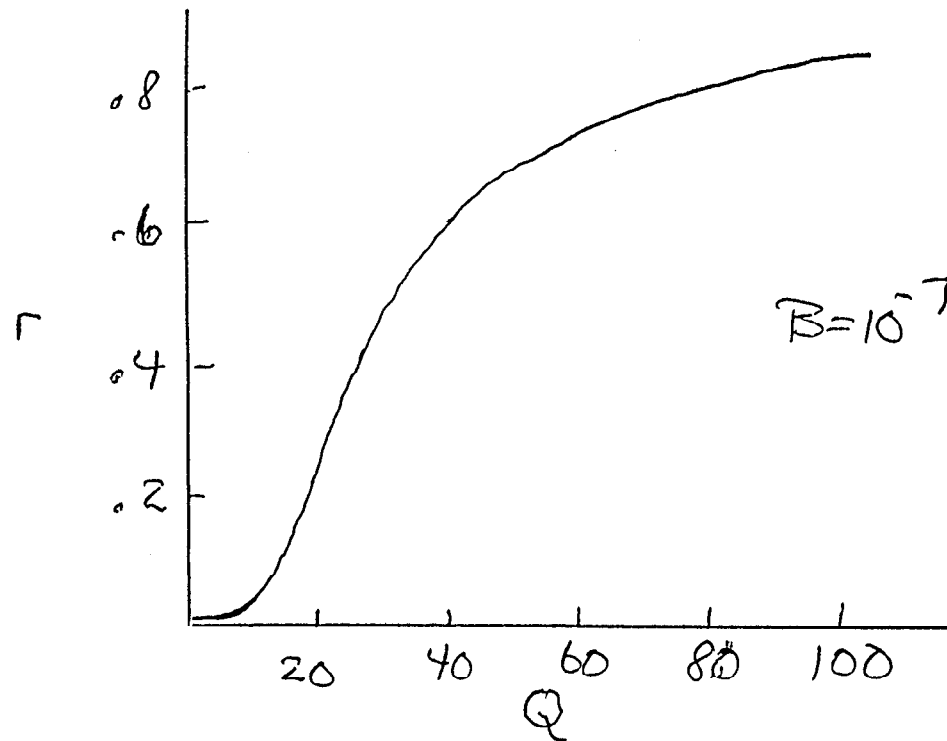
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Linear theory is only an indicator of when to worry

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What we see in experiments is determined nonlinearly.

Example: gas bag Nova experiments SRS $2 \times 10^{15} \text{ W/cm}^2$.12ncr

Q same

$\frac{\nu_i}{\omega_i} \approx .2$	$r \approx 10\%$
$\frac{\nu_i}{\omega_i} \approx .01$	$r \approx .2\%$

Nova small hohlraums test our understanding of high electron density and temperature plasma physics



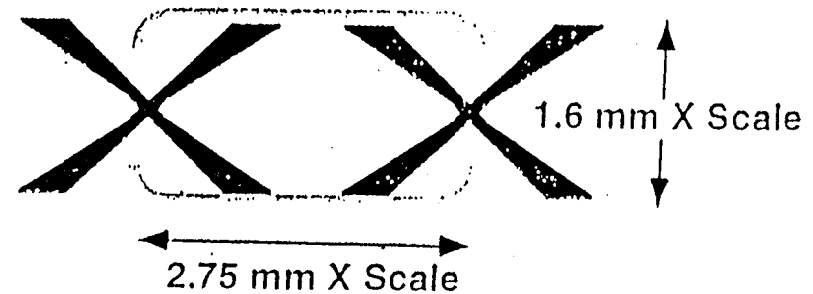
Targets:

Scales 1, 3/4, 5/8, 1/2, 1/4
(X $r=0.8\text{mm}$, $l=2.75\text{mm}$)

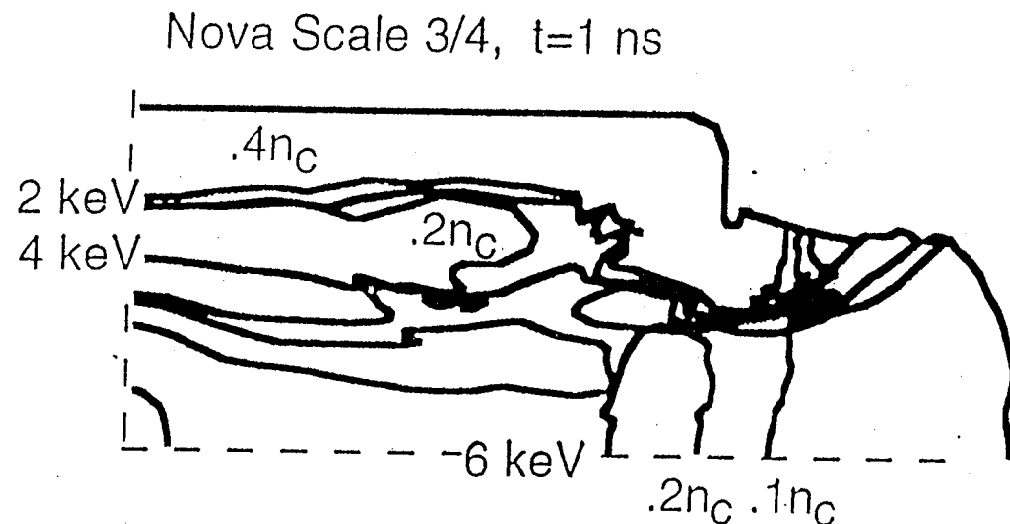
Laser:

25 TW / 1ns in 10 beams

Spotsize at best focus ~ 80 microns



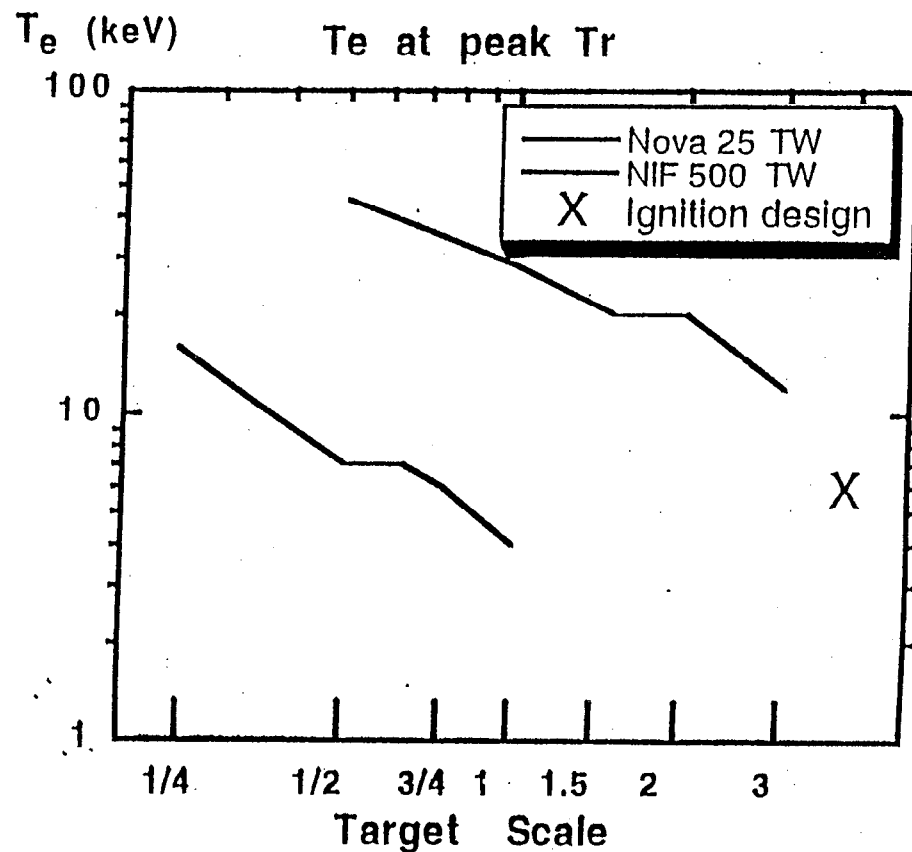
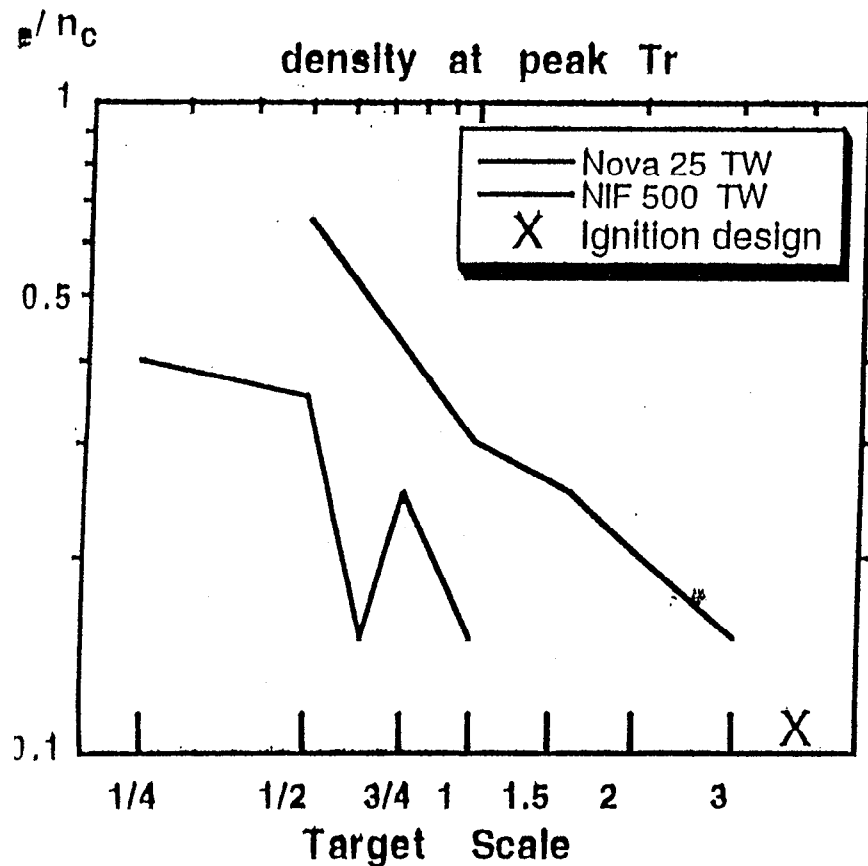
The fill plasma in these targets is hot and dense by the time of peak radiation flux



Nova small hohlraums test density and temperature constraints for NIF hohlraum designs



- Small hohlraums on Nova allow us to access fill densities, plasma temperatures, and radiation temperatures that exceed those in the baseline NIF ignition designs



Powers

The SBS levels in the size scaling experiments were low (T. Orzechowski et al, 1996)

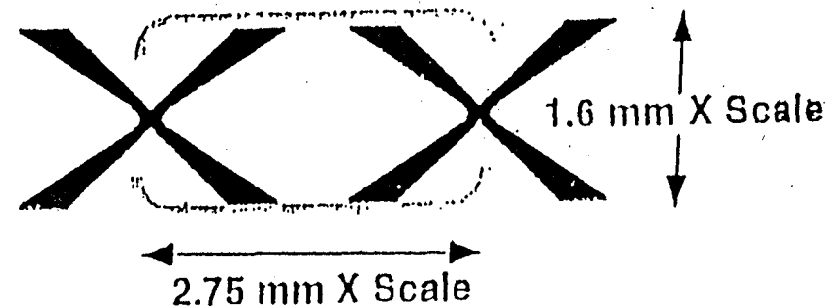


Targets:

Scales 1, 3/4, 5/8, 1/2, 1/4
(X r=0.8mm, l=2.75mm)

Laser:

25 TW / 1ns in 10 beams
Spotsize at best focus ~ 80 microns



hohlraum	FABS	FABS + NBI
scale-1 (w/o ϕ -plate)	20 J	32 J
scale-1 (ϕ -plate)	14 J	32 J
scale-3/4 (w/o ϕ -plate)	28 J	78 J
scale-3/4 (ϕ -plate) *	32 J	76 J
scale-5/8 (w/o ϕ -plate)	53 J	140 J
scale-5/8 (ϕ -plate)	36 J	out of ~1400 J

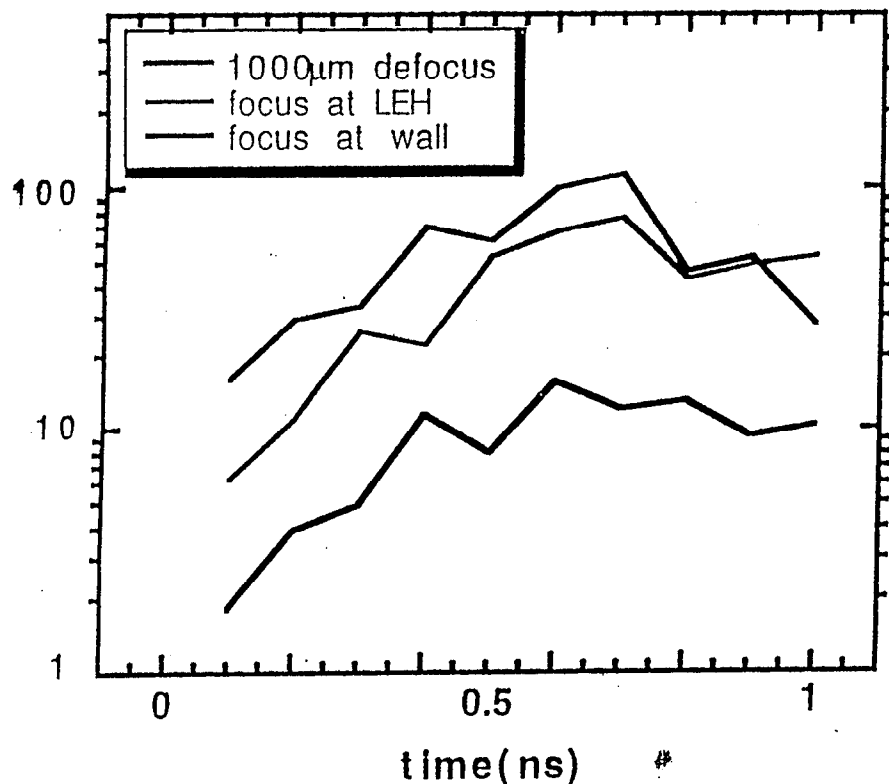
Laser beams focused in the LEH

The measured SBS backscatter fraction is $< 5\%$ for Scale 3/4 hohlraums

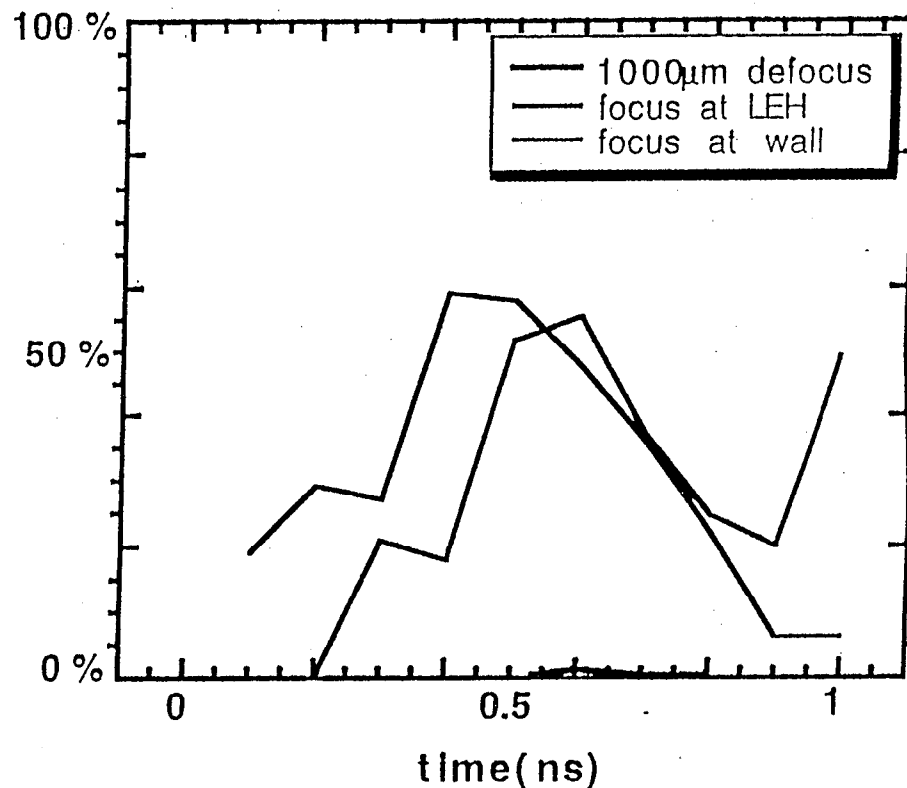


- Linear gain calculations predict large gains and reflectivities

calculated SBS gain coefficient



calculated SBS backscatter fraction



- SBS may be suppressed by SRS through pump depletion and/or Langmuir wave decay instabilities.
- filamentation may reduce the effective intensity by spraying the beam

SRS was sizeable with unsmoothed beams, but much reduced with RPP smoothed beams

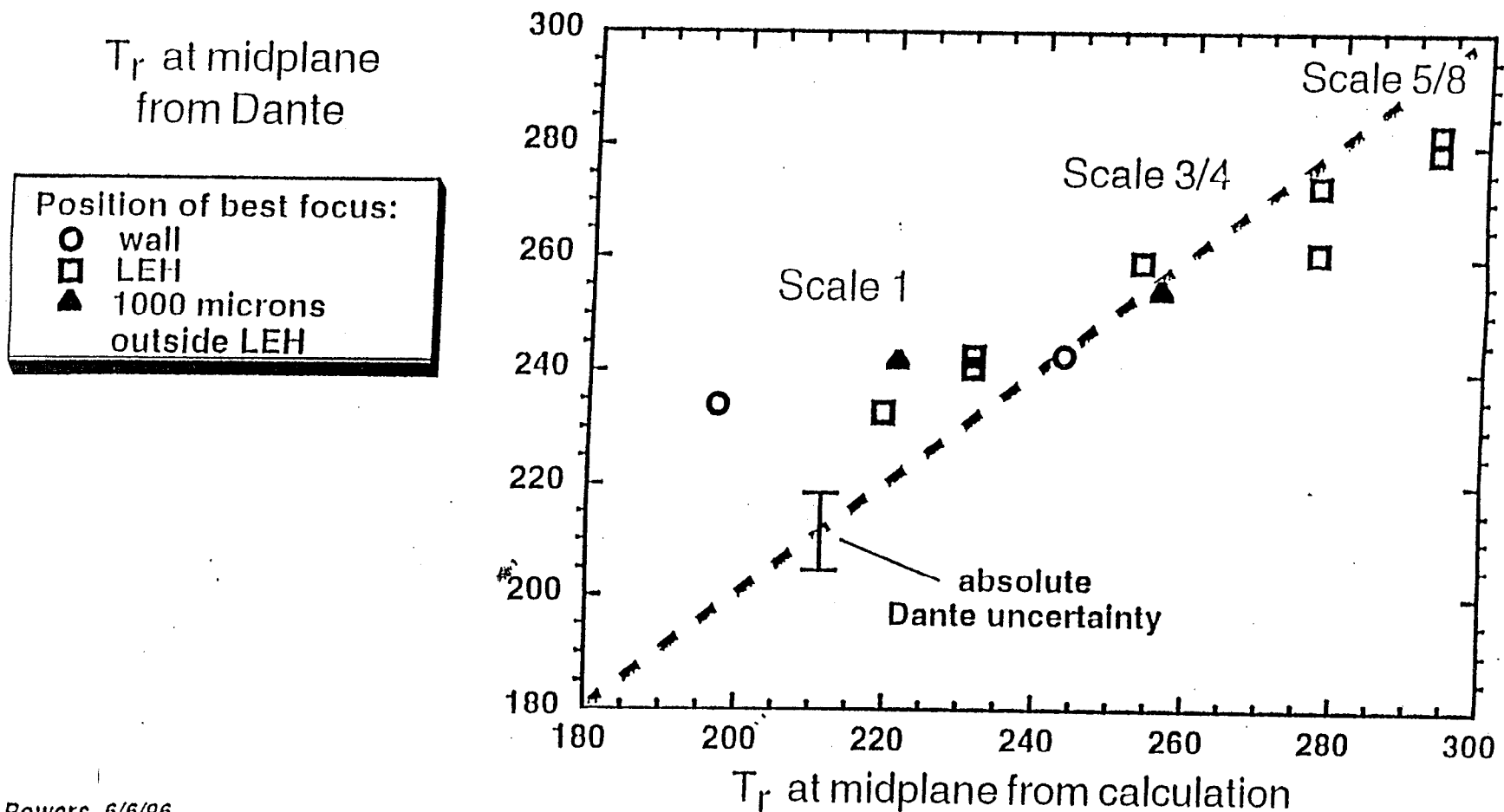


hohlraum size/focus	T_{wall}	T_{hot}	E_{hot}	E_L	$E_{\text{srs}}/\text{beam}$	$E_{\text{abs}}/\text{beam}$
scale-1/LEH	241 eV	41 keV	518 J	28 kJ	437 J	32 J
scale-1/ ϕ -plate	243 eV	36 keV	422 J	27 kJ	26 J	32 J
scale-3/4/LEH	273 eV	36 keV	1.3 kJ	28 kJ	455 J	78 J
scale-3/4/ ϕ -plate	261 eV	38 keV	850 J	28 kJ	48 J	76 J
scale-5/8/LEH	282 eV	40 keV	1.3 kJ	29 kJ	394 J	140 J
scale-5/8/ ϕ -plate	279 eV	40 keV	1.0 kJ	29 kJ	175 J	90 J
scale-1/-1000 μm	242 eV	38 keV	40 J	26 kJ	78 J	12 J
scale-1/LEH	233 eV	41 keV	230 J	27 kJ	245 J	20 J
scale-1/wall	234 eV	55 keV	390 J	29 kJ	520 J	76 J
scale-3/4/-1000 μm	254 eV	39 keV	400 J	26 kJ	130 J	36 J
scale-3/4/LEH	259 eV	40 keV	940 J	27 kJ	420 J	110 J
scale-3/4/wall	243 eV	56 keV	490 J	27 kJ	430 J	50 J

When SRS losses are taken into account, measured and calculated hohlraum temperatures agree for hohlraum scales $> 5/8$.



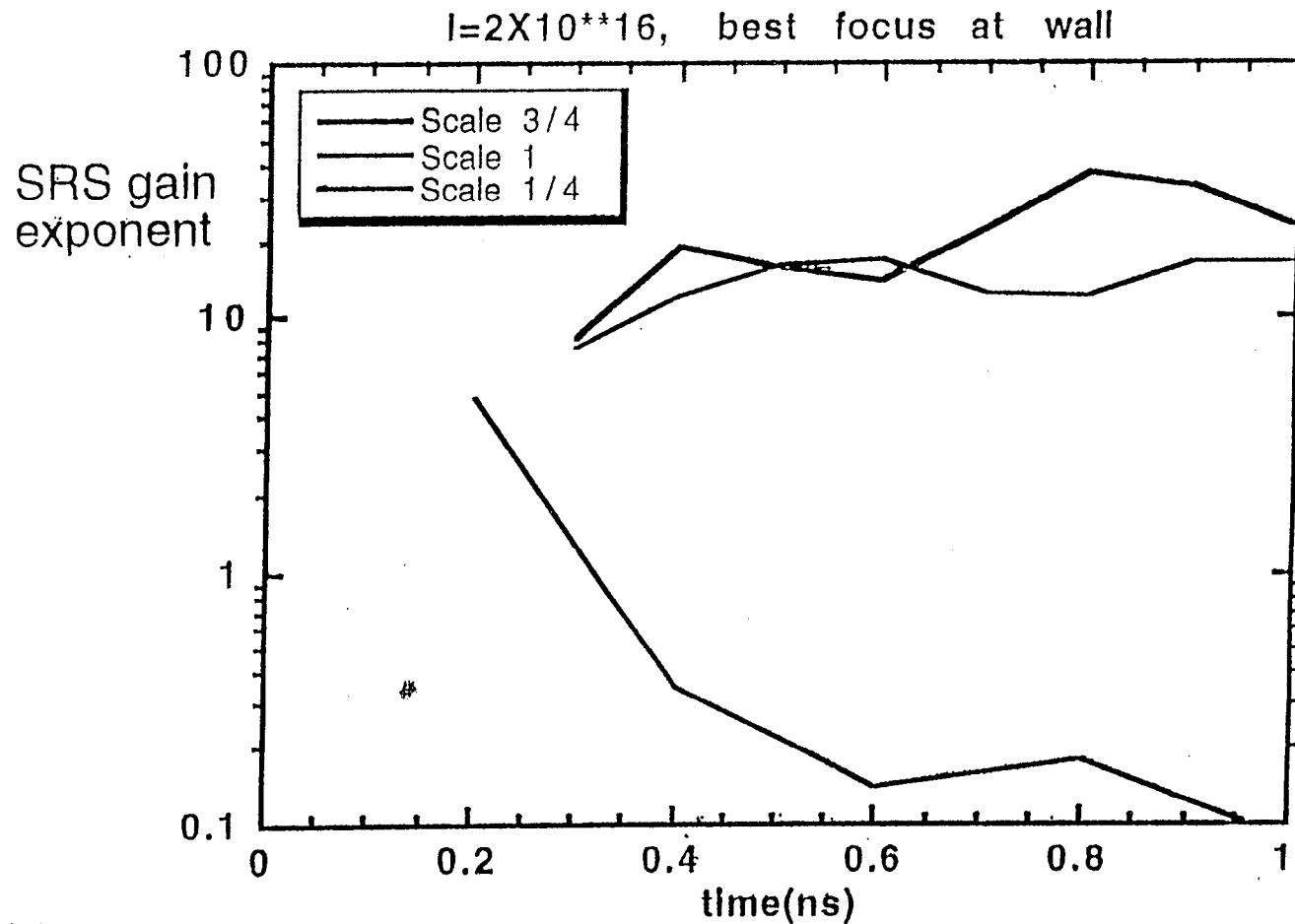
- The calculated interior hohlraum T_r is 15-20% higher than the wall temperature at the midplane
- The Scale 5/8 T_r peaks before the end of the laser pulse (diagnostic hole closure?)



Filling to $n_e > n_c/4$ results in qualitatively different SRS behavior in the Scale 1/4 Nova hohlraum

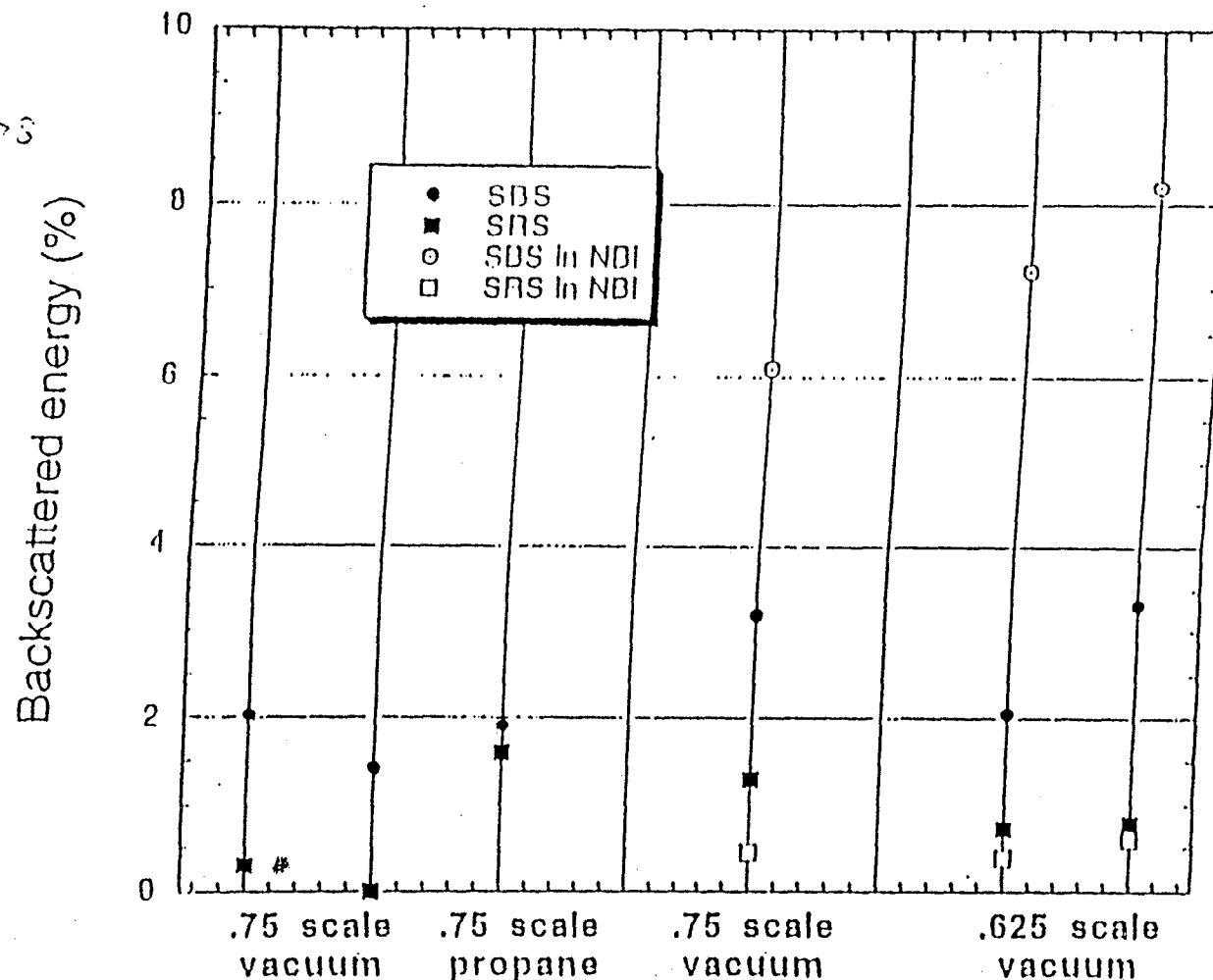


- When the hohlraum fill density exceeds $n_c/4$, the length of plasma that supports SRS is short
- Strong filamentation would create density depressions with $n_e < n_c/4$ (not in calculations)



--- PS 22 with 10 KPPs ---

Similar results
with striped pulses



Brillouin near backscatter seems to be higher

We have to reprocess the data with recent FABS diode calibration

N. Dague et al, 1997

A nonlinear scaling model for strongly-driven SBS has been proposed

Better agreement with observed dependences of SBS reflectivity on intensity, plasma density, length, and f number

See manuscript by Krueer et al

Improved calculations are needed

Strongly-Driven Laser Plasma Coupling

W. L. Kruer, E.M. Campbell, C.D. Decker, S.C. Wilks, J. Moody, T. Orzechowski, L. Powers, L. J. Suter

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550

B.B. Afeyan
Polymath Associates

N. Dague
Commissariat a l'Energie Atomique, Bruyeres-le-Chatel

Abstract

An improved understanding of strongly-driven laser plasma coupling is important for optimal use of the National Ignition Facility (NIF) for both inertial fusion and for a variety of advanced applications. Such applications range from high energy x-ray sources and high temperature hohlraums to fast ignition and laser radiography. We discuss a novel model for the scaling of strongly-driven stimulated Brillouin and Raman scattering. This model postulates an intensity dependent correlation length associated with spatial incoherence due to filamentation and stimulated forward scattering. We first motivate the model and then relate it to a variety of experiments. Particular attention is paid to high temperature hohlraum experiments, which exhibited low to modest stimulated Brillouin scattering even though this instability was strongly driven. We also briefly discuss the strongly nonlinear interaction physics for efficient generation of high energy electrons either by irradiating a large plasma with near quarter-critical density or by irradiating overdense targets with ultra intense laser light.

Introduction

The coupling of intense laser light with plasmas is an extremely rich and challenging topic. The coupling mechanisms¹ span the gamut from inverse bremsstrahlung and linear mode conversion to many nonlinear optical processes. These include stimulated Raman scattering (SRS) from electron plasma waves, stimulated Brillouin scattering (SBS) from ion sound waves, and laser beam self-focusing and filamentation. These processes depend upon laser intensity and produce effects such as changes in the efficiency and location of the absorption and generation of very energetic electrons. Depending on the application, one wishes to either minimize or maximize various nonlinear processes.

Laser plasma coupling is a very important constraint for the conventional approach to inertial fusion. Figure 1 is a schematic showing the

Nova experiments are hopeful

Nonlinear scaling model is hopeful

Key question: what happens in NIF scale 1? (4x larger than related nova experiment)

Some next steps are outlined

This strongly-driven regime is relatively unexplored
-----LLNL

$$n \gtrsim .25 n_{cr} \quad T_e \sim 15-20 \text{ keV}$$

Both SBS and Filamentation very strongly driven

$$Z(v_{os}/v_e)^2 > 1 \quad (>> 1 \text{ in higher intensity speckles})$$

Plasma issues include

Interplay between SBS and Filamentation--SBS levels
2D and 3D Hybrid PIC simulations and F3D

Ion-ion collisions, effect of interpenetrating plasmas
on hohlraum plasma conditions
Rambo codes with collisions à la Rambo PRL

Modified electron distributions, effects on inverse
bremsstrahlung and speckle decorrelation
Fokker-Planck calculations à la Afeyan PRL

ZOHAR provides laser-plasma simulation at the most fundamental level of description.



- Zohar's model equations¹ provide a fully kinetic and nonlinear description:
 - Ampere-Faraday-Maxwell fields
 - Relativistic particle dynamics
 - Particle-in-cell coupling of particles to fields
- The BZohar package optimizes for Brillouin scatter². Substitutions:
 - high frequencies: time-enveloped fields and currents
 - low frequencies: nonlinear Boltzmann electrons + PoissonMuch-larger time steps resolve picoseconds rather than femtoseconds.
- Only Zohar provides first principles modeling of scattering instability saturation and laser-plasma interaction at very high intensities.

¹As described in "Plasma Physics via Computer Simulation", Birdsall and Langdon.

² "Resonantly Excited Nonlinear Ion Waves", B. I. Cohen, B. F. Lasinski, A. B. Langdon, E. A. Williams, *Physics of Plasmas* 4, 956-977 (1997).

Moderate stimulated Raman scattering appears tolerable
-----LLNL

$$\text{SRS} \quad \omega_0 = \omega_{\text{sc}} + \omega_{\text{pe}}$$

In very hot plasmas, SRS is mainly from $n \sim .2 - .25 n_{\text{cr}}$

- *significant absorption of scattered light

- *most energy stays in hohlraum

- *hot electrons may be useful (Suter)

SRS especially significant for hohlraums filling to $\sim .25 n_{\text{cr}}$

Bonus: such experiments also relevant to
hard x-ray sources for NWET

A variety of experiments can be suggested.

-----=LLNL

Janus
or Trident

Higher Z exploding
foil plasma with
 $n > .25 n_{cr}$

code test:
interplay of SBS and Fil.
simulate entire
experiment in 2D

Nova or
Omega Upgrade

smaller hohlraums
with improved
diagnostics

or

denser gas bags
with, say, 2wobeam
to get $n > .25 n_{cr}$

#

Most of these topics are ideal for collaboration with Naval
Postgraduate School students

-----LLNL

Interface NPS students with Lab research projects

--Pool of talented, motivated students

--Very valuable to establish LLNL-NPS connections

Outline of Presentation

-----LLNL

*Nova experiments and scaling models indicate that higher temperature hohlraums are possible with NIF; these are valuable for SSMP

*Strongly-driven laser plasma interaction physics is a key issue for attaining higher temperature hohlraums

*Nova experiments and recent theory are hopeful: next steps are outlined

Appendix

A nonlinear scaling model for strongly driven SBS

Towards a new scaling model.....



- Linear scaling clearly does not generally work
 $r \sim B \exp(k \cdot I \cdot L / v)$
sometimes qualitatively wrong
- Evolution in “improvements”
 - speckle statistics (sum over intensity distribution)
Rose et al,
 - damping not necessarily linear Landau damping
Rambo et al, Afeyan et al, Rozmus et al,
- Next step?-----replace L with intensity-dependent correlation length^{“#}
 - instability-induced incoherence
 - $I \cdot L$ statistics (Afeyan and Schmitt)
 - spatial incoherence suppresses and results from filamentation

An idealized model for SBS in strongly driven plasmas is illuminating—I



Consider an RPP beam, SBS from heavily damped ion waves

Hypothesis I

Gain is limited by intensity-dependent coherence length (ℓ_{coh}); incoherent regions (different speckles) do not communicate

$$r = \sum_I B \frac{L}{\ell_{\text{coh}}} \exp Q(I, \ell_{\text{coh}})$$

\sum_I average over speckle statistics

$$Q = \frac{\pi}{2} \frac{\ell_{\text{coh}}}{\lambda_0} \left(\frac{\omega_{\text{pe}}}{\omega_0} \right)^2 \left(\frac{v_{\text{os}}}{v_e} \right)^2 \bigg/ \frac{v_i}{\omega_i}$$

A simple model for SBS scaling—II



Hypothesis II

- Coherence length in strongly driven plasma is set by filamentation (perhaps aided by Brillouin forward scattering)

Speckles: $r = f\lambda_0$, $\ell_{\text{coh}} = 8f^2\lambda_0$

- Speckle self-focuses when $r_{\text{SF}} \simeq 2r \frac{v_e}{v_{\text{os}}} \frac{\omega_0}{\omega_{\text{pe}}} < \ell_{\text{coh}} = 8f^2\lambda_0$
- Self-focusing of speckles (filamentation) \rightarrow angular spread
- Assume process goes to marginal stability

i.e., $r_{\text{SF}} \simeq \ell_{\text{coh}}^* \rightarrow f \simeq \frac{1}{4} \frac{v_e}{v_{\text{os}}} \frac{\omega_0}{\omega_{\text{pe}}}$, $\ell_{\text{coh}} \equiv \frac{\lambda_0}{2} \left(\frac{v_e}{v_{\text{os}}} \right)^2 \left(\frac{\omega_0}{\omega_{\text{pe}}} \right)^2$

This model gives scalings closer to strongly driven experiments



$$\text{With } \ell_{\text{coh}} \simeq \frac{\lambda_0}{2} \left(\frac{v_e}{v_{\text{os}}} \right)^2 \left(\frac{\omega_0}{\omega_{\text{pe}}} \right)^2$$

$$Q \rightarrow \frac{\pi}{4} \frac{v_i}{\omega_i}$$

$$r \sim B \frac{n}{n_{\text{cr}}} \frac{L}{\lambda_0} \left(\frac{v_{\text{os}}}{v_e} \right)^2 \exp \left[\frac{\pi}{4} \frac{v_i}{\omega_i} \right]$$

Note weak scaling with n , I , L

The scaling with damping is qualitatively consistent with experiments



- the reflection decreases with damping
D. Montgomery et al, PP (1998) and references therein
- numbers require better understanding of the self-consistent damping and detuning, which depends on
 - fluctuations --modified distributions
 - collisions --plasma composition and mixing
- modest reflectivities can be motivated
Au plasma $n \sim .2 n_{cr}$ L set by absorption length $\sim 300 \mu$
coherence length $\sim 40 \mu$ $\langle dv \rangle \sim .05$ $B \sim 10^{-8}$ $r \sim 5\%$

Issues for model evolution:

LLNL

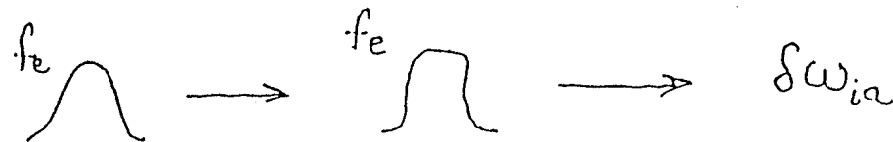
- *when are "speckles" decorrelated?
 - modified distributions and nonlocal transport can play a role
- * coherence length as a function of intensity
 - role of filamentation, instability of filaments, induced gradients, etc.
- * self-consistent damping, collisional effects
- * detuning by long wavelength fluctuations
- * role of plasma-induced spatial incoherence
- *noise levels

Some relevant preprints and reprints are available

Speckles are decoupled by, say, modified distribution functions which change the ion wave frequency



- The next speckle after an intense one most likely has a much smaller intensity
- Heat transport or collisional absorption can produce an intensity-dependent modified electron distribution function, which changes the ion wave frequency



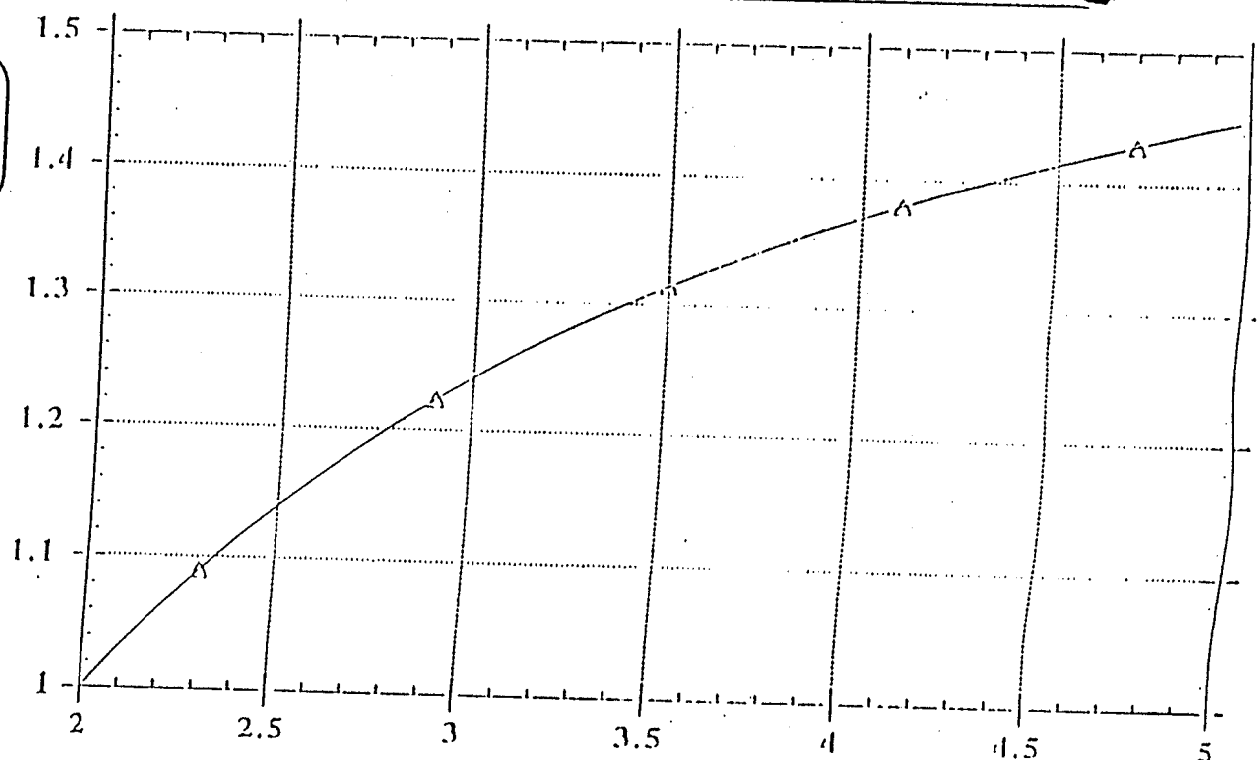
- Variation of the ion wave frequency from one speckle to another disrupts their communication

B.B.Afeyan et. al. PRL 80, 2322 (1998)

In Flat Top Distribution Functions Ions Are Not As Well Shielded: Increased *Effective* Electron Temperature T_e or c_s^2 for IAWs

$$c_s^2|_{\text{flat-top}} = C_{\text{eff}}^2 c_s^2|_{\text{Maxwellian}}$$

$$C_{\text{eff}}^2 = \left[\frac{3\Gamma^2(3/n)}{\Gamma(1/n)\Gamma(5/n)} \right]$$



- The frequencies of ion acoustic waves can be stretched by as much as 20% due to the flattening of the central part of the electron distribution function.
- Passage through regions with various degrees of flattened distribution functions could serve as an additional detuning or saturation mechanism for SRS and LDI. Strongly discriminate against oblique propagation ==> reduce crossed beam gain.
- RPP beams, speckle patterns and enhancements thereof due to filamentation can easily provide the c_s^2 varying medium where SRS gain would be limited.

Other effects contribute to decorrelating speckles and reducing the coherence length



- thermal filamentation
- stimulated Brillouin forward scattering
 - also gives laser beam spraying
 - see experiments by J. Moody and by P. Young
- temporal incoherence
 - for example, by SSD
 - speckles move in time
- fluctuations,[#].....